

## Frequently Asked Questions

# Light and Color

### ***What are the color properties of light sources?***

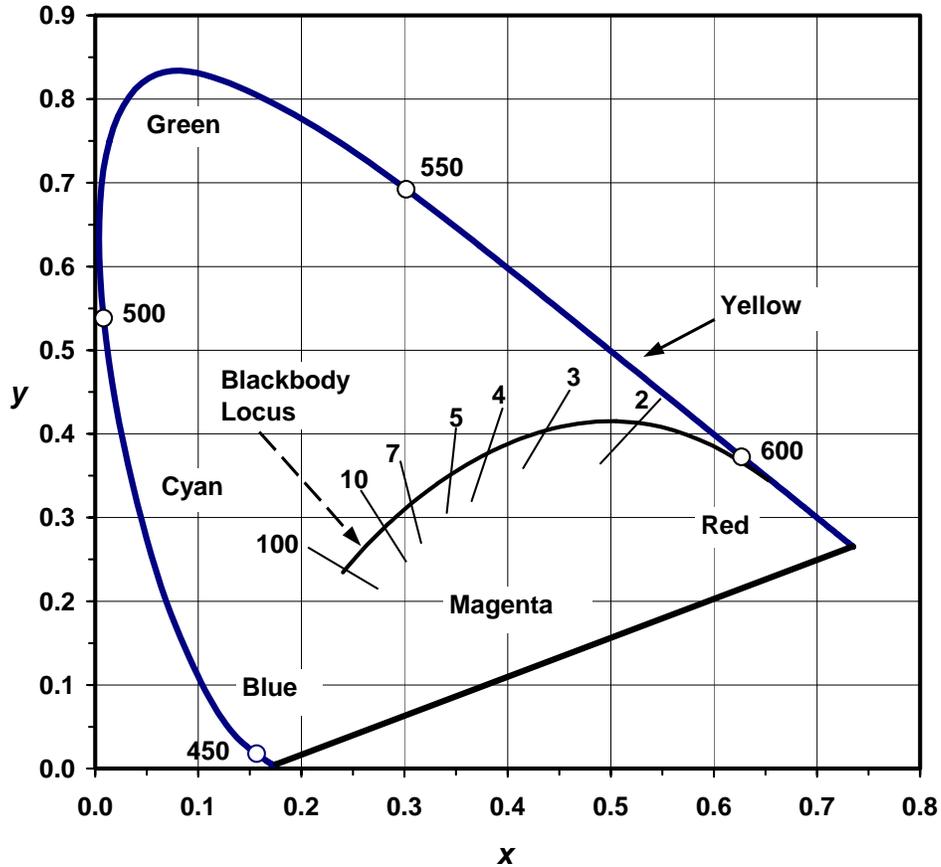
The spectral power distribution (SPD) of a light source carries a complete description of the color properties of the light source, and all other measures can be derived from this. However, it is not easy to interpret a SPD curve. Simpler and more convenient measures are necessary for everyday applications.

### **Chromaticity Coordinates**

A chromaticity diagram is a 2-dimensional plot of all possible colors of light in terms of hue and saturation dimensions (or dominant wavelength and purity) but independent of magnitude, i.e., independent of lumens, lux, footcandles, etc. The point on this diagram where any specific light source color is plotted would be identified by the chromaticity coordinates of that point. Commonly, light source colors are plotted on the 1931 CIE Chromaticity Diagram (see Figure 1) in terms of x and y coordinates (x,y), but there are other chromaticity diagrams used for various special purposes. The boundary of all possible colors on the chromaticity diagram is a closed curve formed by plotting the spectral colors, i.e., those due to single wavelengths, and by plotting a mix of two wavelengths at the ends of the spectrum.

It is important to note that a chromaticity diagram is not a color appearance diagram although the highly chromatic or saturated chromaticities near the boundary tend to be reasonably consistent in terms of color appearance. For chromaticities toward the center of the diagram (colors that are not highly saturated), other aspects of vision such as luminance contrast, color contrast, and adaptation will affect the color appearance. Chromaticity coordinates have many uses. One is to suggest the relative appearance of two or more colors. Also, if two different lights are additively mixed, the chromaticity of the resultant light must lie on a straight line between the chromaticities of the original lights. If more than two lights are additively mixed, the chromaticity of the resultant light must be within the polygon whose vertices are the original chromaticity coordinates of the various lights. It is possible to calculate the resultant chromaticity coordinates of an additive mix from the individual chromaticity coordinates.

The chromaticity of a light source is derived from the SPD of the light; any given SPD has only one set of chromaticity coordinates. However, the converse is not true. There are an infinite number of SPDs that can produce any chromaticity. The most important conclusion from this is that the chromaticity coordinates tell nothing about the spectral makeup of the light and therefore does not tell anything about how the light will affect the color appearance of lighted objects.



**Figure 1 - 1931 CIE Chromaticity Diagram (CCT lines crossing the Blackbody Locus are labeled in thousands of K.)**

### **Color Temperature**

It is not easy to mentally interpret the appearance of light using chromaticity coordinates. A single number scale would be much easier to visualize. A common single number description for the color of light from a light source is known as color temperature (CT). It indicates the color appearance of the light source when it is viewed directly as well as the color of the light when reflected from a neutral surface. CT indicates a limited set of chromaticity coordinates that fall along a curved line in the central region of the chromaticity diagram. This is the general region where nominally white light sources would plot. CT also suggests the hue of these unsaturated colors when viewed in isolation or at least when not strongly influenced by adaptive or inductive effects. CT is the same measure that is used to describe the quality of photographic lighting and the color balance of photographic films. The CT usually relates to the color impression of a lighted space, especially if the objects in the space are not highly chromatic.

The idea behind CT is to have a continuous range of colors passing through the region of a chromaticity diagram where whitish light sources can be plotted. Then the light to be evaluated is compared to this range, and the point on the range that matches it is identified. A convenient reference is that of a blackbody, a radiating object that is used

for many purposes in science. The values of using the blackbody are (1) that the blackbody is consistent and well known, (2) that its radiation and color can be calculated quite easily, and (3) that the color of its radiated light depends only on a single number, its temperature. The temperature is given in units of the kelvin where the Kelvin temperature is the Celsius temperature plus 273. In the past, the unit was the degree kelvin (symbol, K), but it is now simply the kelvin (symbol, K). This is mostly background information because in applications we associate the CT value with appearance and need not be concerned with the actual temperatures. If there were another well-known single number scale of color going through the central region of the chromaticity diagram, we could have used it and never mentioned temperature. Needless to say, the thermal temperature of the actual light source is not the temperature indicated by the value of its CT although they may be similar for some light sources.

Conceptually, color temperature is found by placing a blackbody source next to the light source and adjusting the blackbody's temperature until the color of the two match. A plot of all possible blackbody temperatures is a line on the chromaticity diagram, and this line is called the blackbody locus. The normal procedure for finding the CT of a light source is to plot its chromaticity and identify where the point falls on the blackbody locus. One problem immediately becomes obvious. What do you do if the chromaticity of the light source does not fall on the blackbody locus but rather is just somewhat near the locus? Well, if you were adjusting the temperature of the blackbody and observing it and the light source, you would get the closest possible match even if you couldn't get an exact match. Now the term for the blackbody temperature at this closest possible match would be *correlated* color temperature (CCT) to indicate that the match was not exact. Lines of constant CCT have been drawn across the blackbody locus on the chromaticity diagram so that one can still simply plot the chromaticity of a light source to find its CCT. These lines represent the closest match at various points along the blackbody locus. You can still do this graphically today, but there are many color analysis computer programs that will save you the work. The concept of closest match, and therefore of CCT, becomes more and more meaningless the farther the chromaticity coordinates get from the blackbody locus.

Very few lamps will have chromaticities exactly on the blackbody locus, and therefore most lamps are actually described in terms of CCT rather than CT. Frequently, someone will fail to say correlated, but you can normally infer that it is implied. Some incandescent lamps are very close to the blackbody locus, and it is reasonable to describe them in terms of CT. If one wants to have different types of lamps in an area but wants them to appear similar in color, then the lamps should have the same or similar CCTs. If two lamps have the same CCT, it does not mean that they will have exactly the same color appearance because their chromaticities can be at different points along a line of constant CCT. For reasons that are beyond and not directly relevant to the present discussion, two lamps with the same chromaticity coordinates may appear almost the same but be distinguishably different.

## Examples of Various Correlated Color Temperatures

Source	Approximate CCT
heating coil on electric range top	800 K
candle	1800 K
high pressure sodium lamp	2100 K
household incandescent lamp	2800 K
tungsten halogen lamp (general lighting)	3000 K
tungsten halogen lamp (projection)	3300 K
cool white fluorescent lamp	4100 K
daylight (sun + sky)	5500 K
north skylight	10,000 - 20,000 K
For additional examples refer to lamp catalogs; many give the CCTs of various lamps.	

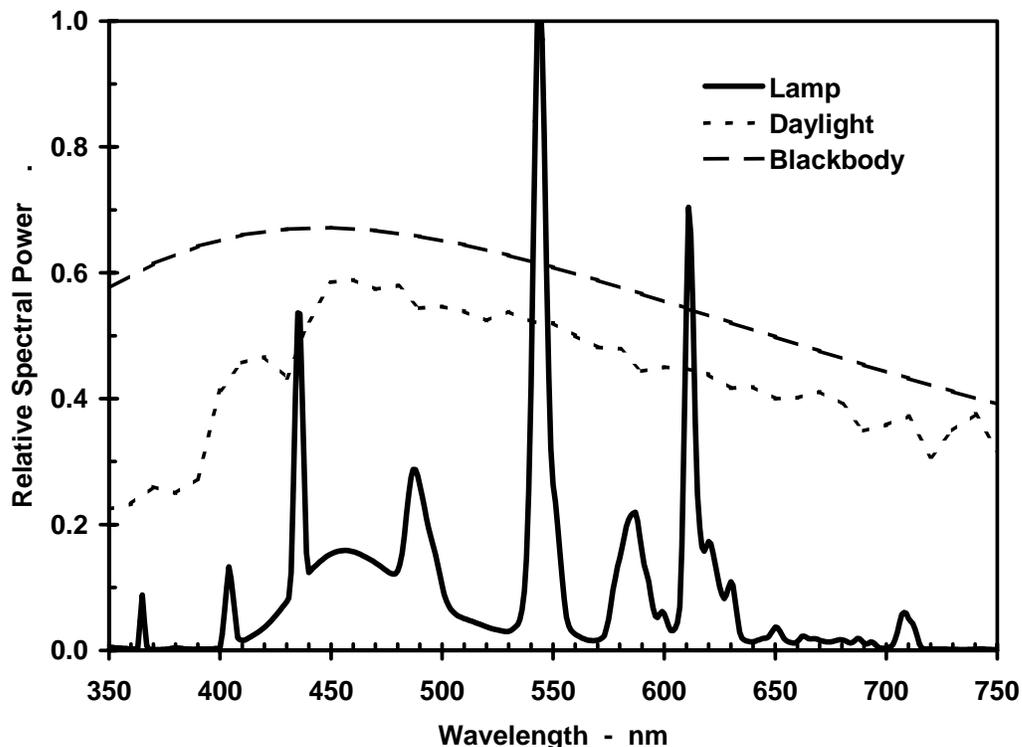
Conceptually, a blackbody can be thought of as an object that is black when cold but, as it is heated, changes color continuously from a deep red to reddish-orange, to orange, to yellow, to yellowish-white, to white, to bluish-white, to blue. Identifying a light source with a point on this scale not only describes the light source color but also is an indication of where the light appears along the (psychological) scale of warm to cool. Light of lower color temperatures is interpreted as having a warmer appearance or ambience while light of higher color temperatures is interpreted as having a cooler appearance. For example, an incandescent lamp at about 2800 K normally is judged warm while light from the blue sky, possibly about 12,000 K, would be judged cool. Observe that the terms warm and cool are relative, and the neutral point (white) between these is not fixed on the CT scale. To a great extent, white depends on the color adaptation of the eye and the various sources of light in the space. As an example, light from either a 3000 K or a 4100 K fluorescent lamp generally is accepted as white light when it is the principal light source in a space. However, if the two lamps are seen next to each other, the 3000 K appears warm (yellowish) while the 4100 K appears cool (bluish); white is judged somewhere between. Now if the 4100 K lamp is seen next to a 5500 K fluorescent lamp, the 4100 K lamp will appear warm. Unsaturated colors of light are generally seen as relative to some frame of reference. As a reminder, a high color temperature light source is interpreted as a psychologically cool light while a low color temperature light source is interpreted as a psychologically warm light.

### **Color Rendering Index**

While color temperature is an indicator of the appearance of light, it tells nothing about the mix of wavelengths present in the light. Yet, it is this wavelength mix of the light that influences the colors of objects when seen under the light. Most people are aware of this, at least in particular circumstances. For example, a navy bluecoat generally appears dark blue in daylight but almost black under incandescent light. The coat absorbs most wavelengths of the incident light but reflects a small amount of incident blue wavelengths. Daylight is rich in blue, and the small amount of blue that is reflected can be seen. However, incandescent light is relatively weak in blue wavelengths, little blue is reflected, and the coat appears black.

The color quality of the light is completely described by the spectral power distribution (SPD) of the light, a record of the amount of power at each wavelength throughout the visible spectrum. This SPD is complex and difficult to

directly interpret. Figure 2 shows the SPD of (1) a 6500 K CCT, 85 CRI triphosphor fluorescent lamp, (2) daylight at 6500 K CCT, and (3) a blackbody radiator at 6500 K CT. Although these lights appear to have very similar colors, it is easy to anticipate that each may have a different effect on the colors of reflective surfaces.



**Figure 2 - Spectral power distributions of three light sources at 6500 K correlated color temperature.**

While the effect of a light source on object appearance is related to its SPD, one wants for practical applications some simpler and more easily interpretable characteristic of the light. One measure in general use is the Color Rendering Index (CRI). Succinctly, the CRI is an indicator of how the light source spectrum affects (i.e., renders) an object's color.

It is important to recognize that objects do not have inherent colors. They have reflectance properties whereby each wavelength in the spectrum of incident light is absorbed or reflected to a varying extent. The appearance of objects depend principally on the interaction of the light source spectrum with their reflectance properties, but many other factors come into play such as adaptation, induction, expectation of the observer, etc.

After WWII incandescent lamps were replaced by fluorescent lamps as the common indoor light source. It was obvious that a large variety of SPDs would be added to the previously ubiquitous incandescent SPD and that a

simple metric would be required for applied lighting considerations. Although there were earlier alternative proposals, the CRI was the first metric that appeared to have practical value and gained wide acceptance.

In simplified form, the general concept was that a single number can't convey much information. What it can do best is tell you how close or how far you are from a reference source. Color experts held meetings over several years to view a large range of "natural" color objects under various light sources. Appearance of each color sample under a light source was evaluated and compared with its appearance under a reference light source that was essentially blackbody radiation or daylight. This type of reference was chosen because it has a fairly "smooth" SPD and can be adjusted to be visually similar a large range of whitish lamps. The CCT of the reference light was always matched to that of the source being evaluated. This match was necessary to avoid strong adaptation effects that would influence any judgment of color and color differences. The magnitude of difference in appearance of a color sample under a source and under its reference was perceptually judged. A set of 14 color samples was found that would reasonably well predict differences that would be observed if a much larger set of colored objects were used. Finally a method of calculation such that the magnitude of visually judged differences could be reasonably well predicted when the source SPD is known.

The scale was set such that a CRI of 100 represents no perceived difference in color appearance between a sample seen under a light source and under its reference light source. The color difference of a sample using a popularly accepted lamp of the era, the warm white fluorescent lamp, as a reference source represents a CRI of 50. [Small changes in lamps and in computational details put the present warm white lamp at about 52.] The originally judged differences formed an interval scale. Anchoring the values of two points (the 100 value and the 50 value) completely defines the CRI.

The color difference for each sample is determined in three dimensions, e.g., such as represented by hue, chroma, and value. The color rendering of sample  $n$  is designated as  $R_n$ . Samples 1 through 8 are not highly saturated and have various hues (mid-range chroma/value samples roughly spanning the hue circle). The average CRI of these eight samples is called the General Color Rendering Index,  $R_a$ . The term *general* often is neglected in practice. Samples 9 through 12 are saturated red, yellow, green, and blue respectively. Sample 13 represents Caucasian flesh tones, and sample 14 represents green foliage. Samples used for the visual appraisals were Munsell samples once it was shown that these would be reasonably representative of other materials, and the calculations are based on their spectral reflectances.

The lighting industry uses the CRI of lamps as a descriptive color metric, and to keep life simple, it is almost exclusively averaged value,  $R_a$ . This CRI does give limited information, but many people do not understand what this limited information is. A common impression of CRI is: *the higher, the better*, and it is implicit in much of the written literature. However, this is not the case, and the following points should be noted.

$R_a$  does not indicate which colors will change or what the directions of change will be. Considering all 14 CRIs instead of an average of eight is better and will give an indication of which colors change and to what extent, but there is still no information on directions of change.

An  $R_a$  of 100 means that there is no change for the 8 samples. As this CRI value decreases, then ON THE AVERAGE the difference in appearance judged against the reference light source increases. As CRI decreases, either all samples will have a moderate change or a just a few samples will have large change.

CRI differences of less than about 5 generally are meaningless.

CRI was not intended for use below about 50, but if there is an equation, people will use it to extrapolate well beyond the experimental justification. [Contrary to popular belief, the general CRI can go below zero and become negative (to approximately -50).]

Almost everyone seems to be surprised when a light source having a higher CRI is sometimes visually judged to be a "poorer color" than a light source with a lower CRI, but remember, CRI is not a metric of desirability or preference.

CRI values can only be compared of sources with similar CCTs.

$R_9$  is principally a measure of the power above about 630 nm. The evaluated color sample is a highly saturated, strong red. This may or may not be of interest depending on the application. It is not unusual in Europe for  $R_9$  to be included along with  $R_a$  as part of lamp descriptions. However, note that even most of the common high color quality (CRI of 85 or above) fluorescent lamps will have relatively low  $R_9$  values.

### CIE Test Color Samples

Number n	Approximate Munsell Notation	Color Appearance Under Daylight
1	7.5 R 6/4	Light grayish red
2	5 Y 6/4	Dark grayish yellow
3	5 GY 6/8	Strong yellow-green
4	2.5 G 6/6	Moderate yellowish green
5	10 BG 6/4	Light bluish green
6	5 PB 6/8	Light blue
7	2.5 P 6/8	Light violet
8	10 P 6/8	Light reddish purple
9	4.5 R 4/13	Strong red
10	5 Y 8/10	Strong yellow
11	4.5 G 5/8	Strong green
12	3 PB 3/11	Strong blue
13	5 YR 8/4	Light yellowish pink (Caucasian complexion)
14	5 G 4/4	Moderate olive green (leaf green)

My interpretation: CRI is a rough estimate of whether object colors in general will change a lot or a little from their appearance under "plain vanilla" lighting, i.e., a reasonably smooth, continuous spectrum. CRI has nothing to do

with correctness, desirability, or preference. It is easy to show that *preferred* light source colors often are below a CRI of 100. If the CRI is low, look carefully at the source to see if it is acceptable for a specific purpose. If the CRI is high, you are unlikely to be in serious trouble with the appearance of object colors. Except for certain "memory colors" such as skin tones, certain foods, etc., you rarely have a basis for how object colors *should* look in any absolute sense. We often forget that objects do not possess the property of color. What they have is reflective-absorptive characteristics as a function of wavelength. [Obviously, the argument can be made more general by including transmission, diffusion, etc.] Color appearance is influenced by the light source SPD, the adaptation chromaticity, general surrounds, context, etc. CRI is a useful concept, but it is easily abused.

Consider one example, both clear mercury vapor and high-pressure sodium (HPS) high intensity discharge (HID) lamps have nearly the same CRI values, about 20. The mercury vapor lamp is *very* poor in rendering reds, oranges, and purples, but it isn't too bad on other colors. Under clear mercury lighting a person looks as if he were a cadaver or the monster in a horror movie, and you'll never find your red car on a parking lot lighted by clear mercury lamps. It is an unacceptable lamp for general lighting. On the other hand, the HPS lamp degrades most colors except in the yellow-orange region, but this degradation is much less than that of the mercury lamp on the red related colors. If color appearance isn't too important, people can live with HPS lighting. It isn't acceptable in offices or merchandising areas, but it gets by in some industrial situations, on parking lots, etc. Here, the low number warns you to consider color issues carefully.

Conversely, a source with a CRI of 85 will probably get by for most applications unless color is a critical issue. For many color inspection tasks, the particular SPD is critical. In such a case, if a 6500 K daylight is specified for a color inspection task, the required SPD will have a CRI of essentially 100. However, there are many 6500 K sources with CRIs near 100 that will be unacceptable in terms of the SPD.

Finally, note the situation where two light sources may have both the same CCT and the same general CRI but have different SPDs. When compressing the information of a light source's SPD into two numbers, much of the information will be lost. Consequently, the two sources may be expected to influence perceived object colors in different ways. The equality of CCT and of CRI have told you that the sources are similar in color appearance and that, on the average, object colors will change by similar amounts from the common reference source --- nothing more. Remember, CCT and CRI are just guideposts to give you limited information about a light source in very simplified form.

### **Other Simple Metrics**

The measures described above have been standardized both in North America and internationally. There are other metrics for characterizing light source color that have been developed in the literature but that have not been adopted as standards. Two of the more interesting and potentially useful ones are described below.

## **Color Preference Index**

Possibly the most interesting metric is one that potentially measures what most people seem to want the CRI to measure, i.e., predicted preference for a light source in common lighting installations. Recognizing that CRI was not a measure of preference, a preference based system now known as the Color Preference Index (CPI) was developed in the 1960's and 1970's. A survey of studies on color preference, primarily in the psychological literature, was used to determine desirable shifts in color for common object colors. The method for determining the CPI of a light source is analogous to that for the CRI in the sense that a comparison is made for color samples evaluated under the light source and then under a reference source (the same reference that is used for CRI of the source). The CPI increases when the sample colors shift in accord with the preference data, not when color change is reduced. The CPI is a single number result, the weighted average of performance for several test samples. Studies indicated that redder and more saturated human complexion colors are preferred. CRI sample 13 is used to represent complexion. A higher value for CPI is generated when a preferred color shift occurs in relation to the appearance under the reference source. Various studies indicated that in almost every lighting installation, either consciously or subconsciously, human complexion is a very important criterion by which the installation is evaluated. For this reason, the evaluation of sample 13 has 35 percent weighting in the final CPI.

Food colors are probably of next most importance in preference, and studies indicated that there is no significant difference between actual and preferred colors in most cases. CRI sample 2 is taken as representative of the color of butter. Because the color of butter is one of the more critical food colors, it has a 15 percent weighting in the final CPI with a target of no color change. Foliage is another important color, and studies indicated that preference is for a color that is considerably less yellow and is slightly more saturated. CRI sample 14 is used to represent foliage color and is given 15 percent weighting in the final CPI with a target color in the preferred direction. The CRI test colors 1 and 3 through 8 are each given a 5 percent weighting in the final CPI with targets of no change from the reference light source.

The CPI value increases as the expected preference for object colors increases under a light source. The principal proposal for CPI has set a scale such that a clear mercury vapor lamp has a CPI of zero, a very rational decision. The reference source at any CCT has a CPI of 74. The scale is not deliberately bounded at either end. Many relatively common lamps fall in the range of 40 to 75, but some lamps can be above 80. There have not been sufficient studies yet to permit a good interpretation of CPI values or the sensitivity of the scale, but even so it can be useful as added information for relative comparisons between lamps.

It may seem arbitrary to make these changes from the CRI process. However, experimental studies of light source preference have confirmed that the method has quite good validity. It is important to remember that the results apply to a population as a whole and not necessarily to every individual in that population. Also, if there are particular color tasks or objectives in a space, preference based on the rather nonspecific conditions for CPI may not be valid. There are almost certain to be preference differences between cultures, but this has not been adequately explored.

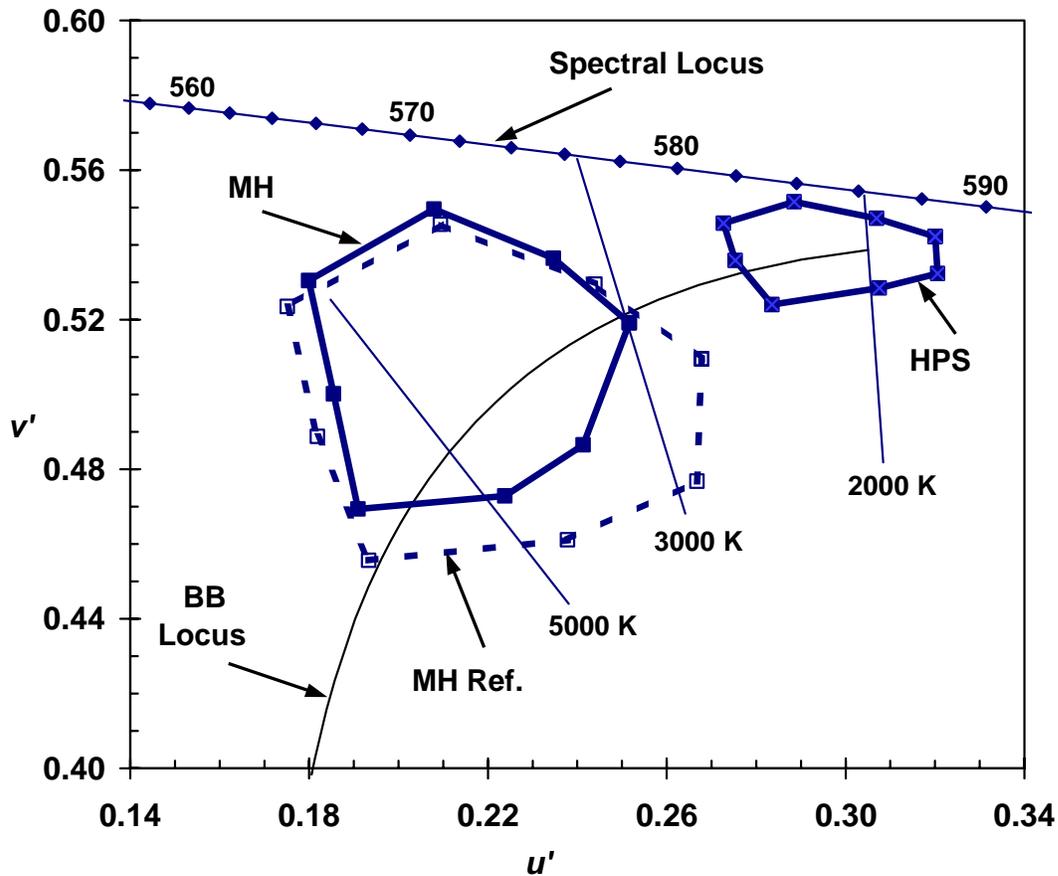
## **Color Gamut**

Color gamut is another potentially useful way to evaluate the color properties of a light source. The concept is to illuminate a set of several color samples by the light source under consideration. The resultant chromaticities of the samples are plotted on a chromaticity diagram. If these chromaticities are considered the vertices of a polygon, then the area enclosed by the polygon is one measure for the separation of the chromaticity points taken as a whole. This area is defined as the gamut area. This area tends to be proportional to the range of colors that can be produced under that light source. In the extreme case of a low-pressure sodium lamp, the gamut area is zero because all samples will reflect the single wavelength of the light, and all sample chromaticities will be the same. The first eight CRI samples of the general CRI are one rational choice for the sample colors because they are spaced around the hue circle. They have been a frequent choice, but other color samples and more than eight samples have been used at various times.

There is one obvious problem in the chromaticity diagram of Figure 1. The colors are not distributed evenly over the area within the spectral boundary. The upper third of the chromaticity diagram is related to green, yellow occupies a very small area, and so on. Consequently, a given gamut area would not have the same interpretation in each part of the diagram. Although it is not possible to have a completely uniform chromaticity diagram, there are diagrams that come closer to the concept where equivalent distances are in some sense perceptually equal. The CIE 1976 UCS Diagram (Uniform Chromaticity Scale Diagram) with coordinates ( $u'$ ,  $v'$ ) is one and commonly has been used for gamut area evaluation. This diagram is analogous to Figure 1, but the shape of the spectral locus is slightly changed and rotated.

As an example, consider the gamut areas of two lamps, a high-pressure sodium lamp (HPS) and a metal halide lamp (MH) shown on a portion of the 1976 UCS chromaticity diagram in Figure 3 using CRI color samples 1 through 8. The HPS lamp has a smaller gamut area than the MH lamp, and it is displaced closer to the spectral boundary. The gamut areas roughly center on the light source chromaticities. These areas correlate with our experience that there is a more limited range of colors seen under HPS than under MH lamps. A comparison between lamps can be made directly in terms of the gamut areas on this diagram.

Another method of evaluation based on gamut area has been proposed. It is to use the ratio of the light source gamut area to the reference source gamut area. Note that this ratio can be either greater or less than one. The gamut area of the reference light source for the MH lamp has been included in Figure 3, and the gamut area ratio is about 0.7. This indicates that the metal halide lamp contracts the available chromaticity color space noticeably with respect to the CRI and CPI reference source at the same CCT. The gamut area ratio of a light source to the reference source is a single stand-alone as opposed to comparing two light sources.



**Figure 3 - 1976 CIE UCS Diagram Gamut areas for high pressure sodium lamp, metal halide lamp, and metal halide reference source. The blackbody locus and lines of constant CCT are included.**

**Concluding Comments**

In one way, the general color rendering index (CRI) can be thought of as an indicator for “naturalness” in the sense that the comparison is with a reference light source at the same CCT whose spectral power distribution is relatively simple and unbiased, and is reasonably uniform. Gamut area is a measure of how widely spaced in chromaticity a particular set of color samples will be when illuminated by a light source. When a consistent set of color samples shows greater or lesser spacing under various light sources, it suggests that the range of possible colors under these light sources also will be greater or lesser. A larger spacing also indicates that color discrimination between similar colors will be easier, and some studies indicate that color gamut area is a good predictor of color naming accuracy.

Although they cannot begin to tell you everything that can be conveyed by a spectral power distribution, these simple single numbers are much easier to interpret. However, for important or critical applications, the final judgment of acceptability for a light source must come from viewing an area lighted by that source. Clearly, one must spend a reasonable time in the area to become adapted to the light, have objects and materials representative of the final

application, evaluate human appearance, etc. Calculations, numbers, computer modeling, or other surrogates will never be as satisfactory as visually evaluating a light source in an environment representative of the ultimate application.